

Structuring polymer gels via catalytic reactions

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We use computer simulations to investigate how a catalytic reaction can induce the formation of a polymer gel. To this aim we consider a polymer solution in which freely-diffusing catalysts convert the originally repulsive monomers into attractive ones. We find that at low temperatures the reaction transforms the polymer solution into a physical gel that has a remarkably regular meso-structure in the form of a cluster phase, absent in the usual polymer gels obtained by a quench in temperature. We investigate how this microstructuring depends on catalyst concentration, temperature, and polymer density and show that the dynamics for its formation can be understood in a semi-quantitative manner using the interaction potentials between the particles as input.

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Many properties of polymer gels that are formed by physical or chemical cross-linking are well understood [1] and thus these materials are used in a multitude of applications [2–8]. But gels are also found in living organisms [9–11] and in these cases the cross-linking is often related to the presence of enzymes, i.e. biological catalysts: In the catalyst-induced gelation of polymer solutions a freely moving catalyst converts the repulsive monomers of the polymers into attractive ones, thus slowly transforming the polymer sol into a gel. This unusual type of mechanism for making gels, or more generally materials, is, e.g., at work in the case of enzyme-induced formation and/or degradation of gels made of proteins [12, 13], peptides [14], or polysaccharides [15], with the prominent example of plant cell walls in which pectins form a gel due to the action of an enzyme [11]. Despite its relevance for many living organisms the structural properties and the dynamics of formation of this type of gel have so far been explored very little.

Although earlier studies on phase-separating systems undergoing chemical reactions evoked the possibility of controlling their steady-state morphology by tuning the interplay between reaction rate and phase separation [16–21], no specific studies of the relevant design rules have been made so far. The goal of the present work is thus to investigate the internal structure of polymeric gels formed via catalytic reactions as well as its evolution with time since this constitutes an important step forward for using these systems in a variety of material science applications.

In our simulations the polymers are modeled as bead-spring chains consisting of A and B monomers that have equal size σ and mass m . Initially the polymers have only repulsive A monomers and the attractive B monomers appear due to the action of freely-moving catalysts (mass $m_c = 5m$ and size $\sigma_c = 2\sigma$). Two B monomers in-

teract with each other through a truncated and shifted Lennard-Jones (LJ) potential of depth ε . The A-A, A-B and catalyst-monomer pairs interact through a Weeks-Chandler-Andersen (WCA) potential [22]. In addition to this hard-core potential, connected monomers interact also by a finitely extensible nonlinear elastic (FENE) potential [23]. More details are in the Supplemental Material. In the following we will express length and energy in units of σ and ϵ , respectively, time in units of $\tau = \sqrt{m\sigma^2/\varepsilon}$ and temperature T in units of ϵ , setting the Boltzmann constant equal to 1.0. A catalyst may convert an A monomer into a B monomer whenever their distance is below $d_{\text{reac}} = \frac{1}{2}(\sigma + \sigma_c) - 0.07$. The bare barrier Δ_{AC} for the reaction of an A monomer with a catalyst is the value of the WCA potential at d_{reac} which is found to be 2.77 (see Supplemental Material).

Simulations are carried out in the NVT ensemble using the LAMMPS software [24]. The simulated systems consist of 408 chains with 100 monomers and a catalyst-to-monomer number ratio N_C/N_m ranging from 0.005 to 0.05, but the data in the main text are for $N_C/N_m = 0.012$. The simulated monomer densities $\rho_m = N_m/L^3$ (with L the size of the simulation box) range from 0.2 to 0.6 (corresponding to monomer volume fractions in the range $[0.1, 0.3]$, relevant for the gelation of polymers). Trajectories are generated using the velocity-Verlet integrator with a timestep $h = 0.003\tau$. All systems are equilibrated before reactions are allowed to occur.

Due to the transformation of the A monomers by the catalysts, the number of B monomers in the system increases with time (main graph of Fig. 1). The fraction of B monomers, ρ_B/ρ_m , first evolves linearly with t for almost three decades, indicating that the catalyst particles are freely diffusing. We find that the monomer conversion rate depends linearly on the catalyst concentration if the latter is less than 0.012 (see Supplemental Fig. S1)

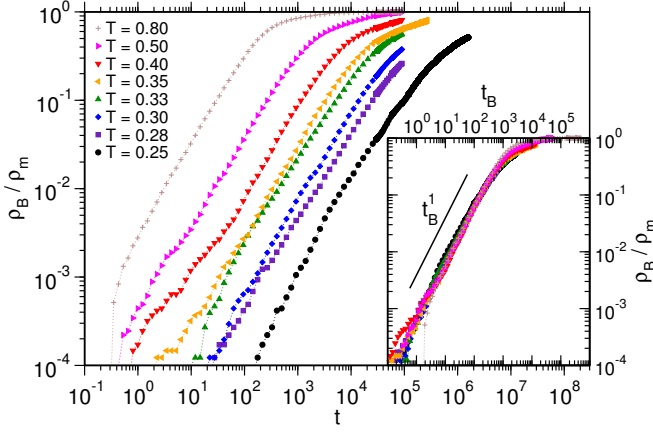


FIG. 1. (Color online) Concentration of B particles as a function of t for different temperatures and $\rho_m = 0.6$. Inset: Same data but now as a function of the reduced time $t_B = t \cdot N_C / N_m \cdot r(T)$ showing that this scaling leads to collapse of the data onto a master curve.

which shows that for these concentrations the exploration of the matrix by the catalyst is not a collective process. At long times the concentration of B monomers saturates since only few A monomers are left and the catalyst particles cannot reach them any more because the former are trapped in dense B regions. The figure also demonstrates that at short times the linear t -dependence is present for all temperatures considered and that it slows down if T is decreased. To determine the influence of temperature on the kinetics of the $A \rightarrow B$ reaction for a given value of the monomer density ρ_m , we have rescaled the curves of the main panel onto a master curve by plotting them as a function of $t_B = t \cdot N_C / N_m \cdot r(T)$, where $r(T)$ is a scaling factor used to collapse the data. (Here the factor N_C / N_m takes into account the above mentioned linear dependence of the reaction rate on N_c .) We find that the T -dependence of $r(T)$ is given by an Arrhenius law with an activation energy $E_B = 2.94$ (see Supplemental Fig. S2) that is independent of ρ_m and is very close to $\Delta_{AC} = 2.77$, the bare potential energy barrier between an A monomer and a catalyst. Hence at short and intermediate t the time scale for the $A \rightarrow B$ conversion is just given by the time needed to overcome this barrier which is independent of temperature and density.

By definition of t_B , systems at different T but with the same value of t_B have the same number density ρ_B of B monomers. Since at low T the presence of the attractive B monomers will give rise to a phase separation, their concentration can be expected to be directly related to a time-dependent driving force for this thermodynamic instability. Thus an increasing ρ_B will drive the system into the coexistence region and consequently induce the phase separation.

The snapshots of the system, Fig. 2, allow to get a qualitative understanding of its evolution with time and

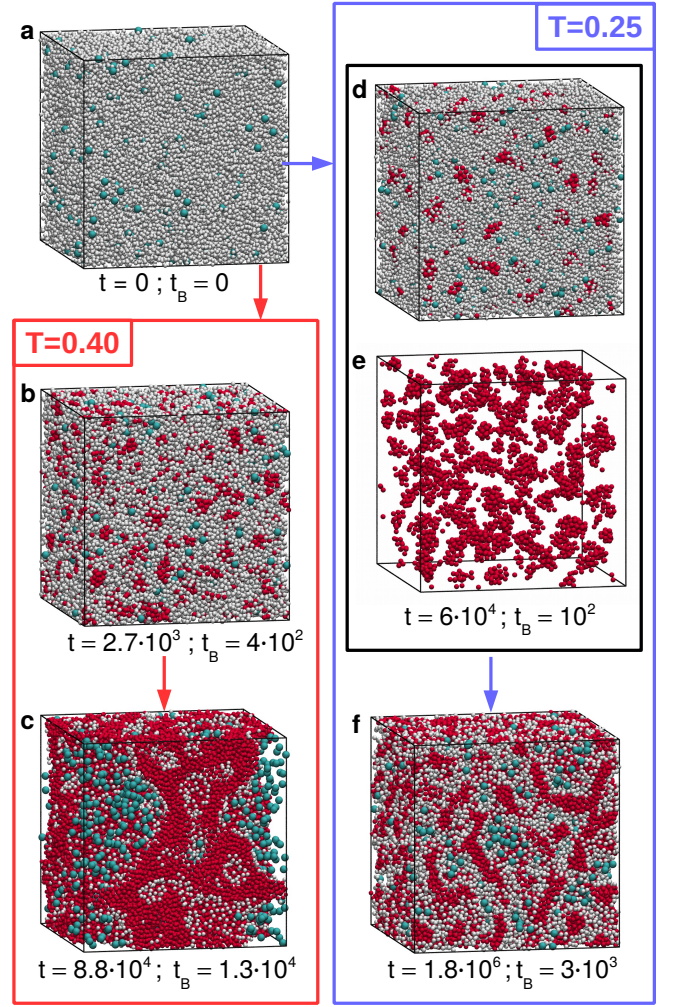


FIG. 2. (Color online) Evolution of the structure at $\rho_m = 0.6$. (a) $t = 0$: Homopolymer solution that contains catalysts (A monomers in white, catalysts in blue). With increasing time, A monomers are converted into B monomers (red) which aggregate and form clusters, panels (b) and (d). At high T and long times the macroscopic phase separation starts, panel (c), whereas at low T the system forms a gel, panel (f). Panel (e) is the same configuration as in panel (d), but now only the B monomers are shown so that the clustering becomes more visible.

indicate that the structure does indeed transform in a manner that is qualitatively similar to a spinodal decomposition: At high T and long times it forms domains that are polymer rich or polymer poor (Fig. 2c) whereas at low T it forms a gel (Fig. 2f). (A side effect of the phase separation is that due to entropic reasons the catalyst particles are expelled from the polymer-rich phase, see Fig. 2c and Supplemental Material.) Most remarkable is the observation that at intermediate times the system shows an unexpected mesostructure that contains clusters of B monomers (see Fig. 2b, 2d, 2e) and in the following we will discuss the t -dependence of this structural evolution

in more detail.

Although a constant ρ_B implies a constant driving force, the *response* to this force and hence the evolution of the system can be expected to depend on temperature. This is certainly true for the formation of the *local* structure since the local energy is expected to be the relevant quantity for this dynamics. To take into account this T -dependent response we make the Ansatz that the relevant time scale which determines the structure of the system at intermediate times is given by $t_S = t_B \cdot s(T, \rho_m)$, i.e. the product of the time scale for the driving force and a factor $s(T, \rho_m)$ that characterizes the dynamic response of the system. We determine this factor $s(T, \rho_m)$ by requiring that systems with the same t_S and ρ_m but at different T have the same structure. This iso-structure time t_S thus allows to compare for short and intermediate times the properties of systems at different temperatures. We emphasize that it is not evident at all that such a time t_S really exists, i.e. that the evolution of the system can be described by just one internal time scale t_S . To test this hypothesis in practice we use $s(T, \rho_m)$ as free parameter to superimpose $S_B(q)$, the static structure factor of the B-particles, where q is the wave-vector.

Figure 3a demonstrates that it is indeed possible to find a scaling factor $s(T, \rho_m)$ that leads to a master curve for the $S_B(q)$ at the different temperatures. If t_S is small there are only very few B monomers and hence $S_B(q)$ is basically flat. With increasing time one finds a peak at $q \approx 7$, corresponding to the nearest neighbor distance between two monomers. At the same time we see a marked peak at $q_p \approx 1.0$. This value is basically independent of time, indicating that the peak is *not* related to a standard coarsening process that shows a growing length scale [25], but is instead directly linked to the clusters of B particles seen in the snapshots [26]. Note that the peak is quite high, indicating that these clusters have a well-defined distance from each other and that the length scale $2\pi/q_p \approx 6$ corresponds indeed to the distance between neighboring clusters seen in the snapshots. It is remarkable that this rather complex q -dependence of $S_B(q)$ is present at all temperatures (but at different times) and that the structure factors can be superimposed with very good accuracy by choosing just one scaling factor $s(T, \rho_m)$. This implies that on the time scale considered the relaxation dynamics of the system can indeed be parametrized by a single internal variable, the iso-structure time t_S . We have found (see Supplemental Fig. S3) that $s(T, \rho_m)$ follows an Arrhenius law with an activation energy $E_s \approx 1.3$ for $\rho_m \geq 0.4$, which is roughly comparable with the well depth $\varepsilon = 1.0$ of the Lennard-Jones potential governing the attraction between B monomers. Hence we can conclude that the dynamic response of the system that leads to the evolution of its structure is directly related to the attraction between B monomers.

Figure 2c demonstrates that at high T the system

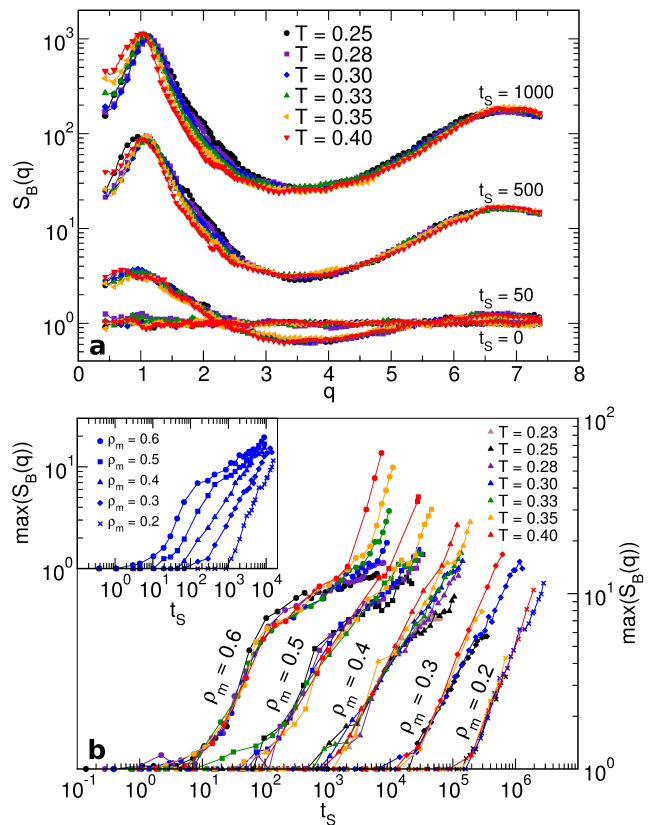


FIG. 3. (Color online) (a) Structure factor $S_B(q)$ at $\rho_m = 0.6$ for different times t_S and temperatures. For clarity $S_B(q)$ is multiplied by 10 and 100 for $t_S = 500$ and $t_S = 1000$, respectively. (b) Evolution of the maximum of $S_B(q)$ as a function of t_S for different values of T and ρ_m . Same type of symbols for same ρ_m , same color for same T . For the sake of clarity the curves are shifted to the right by a factor of 4, 16, 64, and 128 for $\rho_m = 0.5, 0.4, 0.3$, and 0.2 , respectively. Inset: Same quantity at $T = 0.30$ and different values of ρ_m .

makes a complete phase separation, in agreement with the observation that $S_B(q)$ grows at low q a peak (Inset of Fig. 4a), as usual in coarsening systems [25]. For low T , however, the system remains in the disordered state even at long times, i.e. it forms a gel (Fig. 2f). To quantify the evolution of the structure we have determined the height of the peak at $q_p \approx 1.0$, and show its t -dependence in Fig. 3b. For the density that we have discussed so far ($\rho_m = 0.6$, leftmost set of data) the curves for the different temperatures fall at short and intermediate times nicely on a master curve, thus demonstrating that it is indeed possible to define a single time scale t_S that describes the structural relaxation leading to the formation of the clusters. The observed master curve increases first quickly (the t -dependence is basically an exponential) before it crosses over to a much slower (logarithmic) time dependence. For even longer times the curves bend again upwards. This final change in the t -dependence is not related to a growth of the peak at $q \approx 1.0$ but

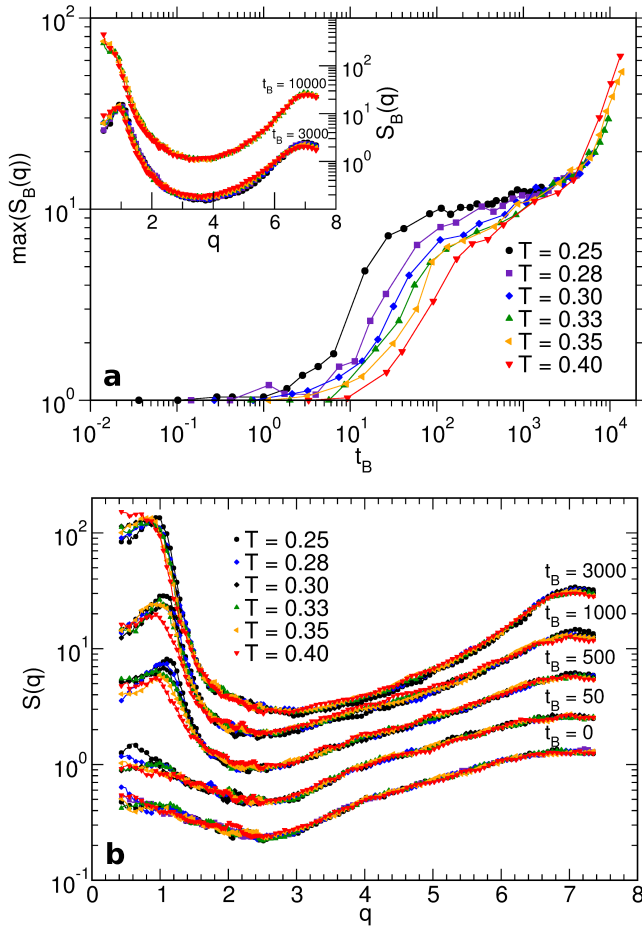


FIG. 4. (Color online) (a) Evolution of the maximum in the static structure factor $S_B(q)$ as a function of t_B for different values of T . Inset: $S_B(q)$ for different values of T and t_B . Note that for clarity $S_B(q)$ for $t_B = 10000$ is multiplied by 10. (b) Total structure factor $S(q)$ at $\rho_m = 0.6$ and different values of T and t_B . Note that for clarity $S(q)$ is multiplied by 2, 4, 8, and 12 for $t_B = 50, 500, 1000$, and 3000, respectively.

instead to the growth of the structure factor at small wave-vectors due to the coarsening that sets in at late times (see Fig. 4a, Inset). Note that the extent of the quasi plateau at intermediate times depends strongly on T and thus, if T is sufficiently low, the final step of the phase separation can be moved to very large times, thus allowing to form a stable gel.

The t -dependence that we have just discussed is for a high density of polymers. If ρ_m is decreased the initial increase of the peak at q_p is delayed because the B monomers are on average farther apart and the plateau at intermediate times is less pronounced (see Inset of Fig. 3b). For low densities the plateau seems to disappear completely, at least in the temperature range that we show here [27]. However, for all cases we can define a ρ_m -dependent scaling factor $s(T, \rho_m)$ that allows to superimpose the peak height for short and intermediate times (main panel of Fig. 3b). Since all of these factors

have the same Arrhenius dependence and the same activation energy if ρ_m is not too small (see Supplemental Fig. S3), we can conclude that the growth of the clusters is completely governed by the B-B interaction.

It is also instructive to study the time-dependence of the structure as a function of the time scale t_B , i.e. as a function of the concentration of B monomers. The t_B -dependence of the height of the peak at $q_p \approx 1$ is shown in the main graph of Fig. 4a from which we recognize that this peak grows faster if T is decreased. This behavior is reasonable since at low T the entropic fluctuations are reduced and hence the system can reach more easily an energetically favorable structure, i.e. form the clusters. For long times, i.e. when the system starts coarsening on the mesoscopic scale, the curves for different T 's superimpose which indicates that the coarsening process is indeed completely governed by the concentration of the B monomers, i.e. the effective attractive interaction between the polymers (see also Fig. 4a, Inset). This is supported by the fact that the total structure factors at large fixed t_B but different T 's superimpose for all wave-vectors (see Fig. 4b for $t_B = 3000$) thus indicating a phase separation driven by the fraction of B monomers, but influenced by the formation of B clusters at short and intermediate times.

Our simulations of this catalyst-induced gelation process show that the resulting polymer gels can have a microscopic quasi-ordered cluster phase, i.e. a structure that is absent in gels that are formed by a quench in temperature or by the addition of a chemical agent. We have found that the details of this process can be understood in a simple manner from the effective reaction rate of the catalyst and the strength of the resulting attraction between the monomers. This understanding will thus allow to produce also in real life gels with such ordered microstructure and hence this catalytic reaction is a new approach to design materials with novel structures and mechanical properties as they are needed, e.g., for scaffolds in tissue engineering [28].

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SUPPLEMENTAL MATERIAL

A: Model and simulation details

Two B monomers interact with each other through a Lennard-Jones (LJ) potential $V_{\text{LJ}}(r) = 4\varepsilon [(\sigma/r)^{12} - (\sigma/r)^6]$ that is truncated and shifted at 2.5σ . Here r is the distance between two monomers and ε is the depth of the potential well. The WCA potential used for the interactions of A-A and A-B pairs is obtained by truncating the LJ potential at $r = 2^{1/6}\sigma$ and shifting it to zero by adding ε . Moreover connected monomers interact by a FENE potential of the form $V_{\text{FENE}} = 0.5kr_0^2 \ln(1 - (r/r_0)^2)$ with $k = 30\varepsilon/\sigma^2$ and $r_0 = 1.5\sigma$. The catalyst-monomer and the catalyst-catalyst pairs interact via a WCA potential.

If the distance between an A monomer and a catalyst particle is less than $d_{\text{reac}} = \frac{1}{2}(\sigma + \sigma_c) - 0.07$, the monomer can be converted into a B monomer. This reaction occurs only with a probability of 10%, since in real systems catalyst activity is less than 100% due to thermal noise and the orientation of the catalytic molecule. Whenever the A to B conversion occurs, a smooth transition (duration 100 simulation steps) from the WCA to the LJ potential is done in which the local energy of the converted monomer and its neighbors of type B is conserved by rescaling their kinetic energies. The ability to perform such reactions between the catalysts and A monomers was added to the LAMMPS software.

B: Effect of the catalyst concentration on the A→B reaction rate

In Fig. S1 we show the influence of the number density of the catalyst particles on the reaction kinetics for different values of T . Note that time is scaled by the catalyst-to-monomer ratio N_C/N_m . We recognize that the curves for $N_C/N_m \leq 0.012$ nicely superimpose, demonstrating that at small concentration the transformation rate of A to B is directly proportional to N_C/N_m . For higher concentrations the reaction kinetics is slightly faster for $N_C/N_m = 0.05$, indicating that collective effects start to affect the transformation dynamics. The cross-over from the linear to the non-linear N_C/N_m -dependence seems to depend only weakly on temperature.

C: Catalytic particles and polymer phase separation

From panel **c** of Fig. 2 we recognize that when the system starts to phase separate on the mesoscopic length scale, most of the catalysts are expelled from the polymer rich phase. This effect is due to entropic reasons since the increasing concentration of the attractive B monomers leads to a tightening of the polymer network and the

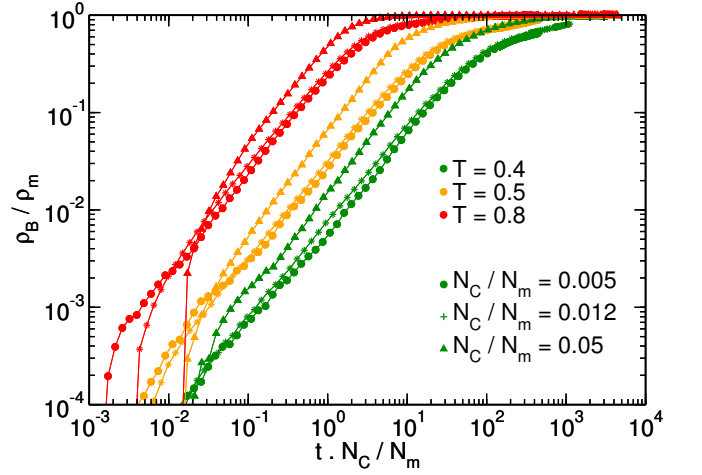


FIG. S1. (Color online) Influence of the catalyst concentration on the A→B reaction rate. For catalyst-to-monomer ratios N_C/N_m below ≈ 0.012 , the transformation rate scales linearly with N_C/N_m and thus the curves for the different concentrations fall on top of each other. Note that same color corresponds to same T and same symbol to same N_C/N_m . To improve the statistics of the results the curves for $N_C/N_m = 0.012$ have been averaged at short times over 8 independent samples.

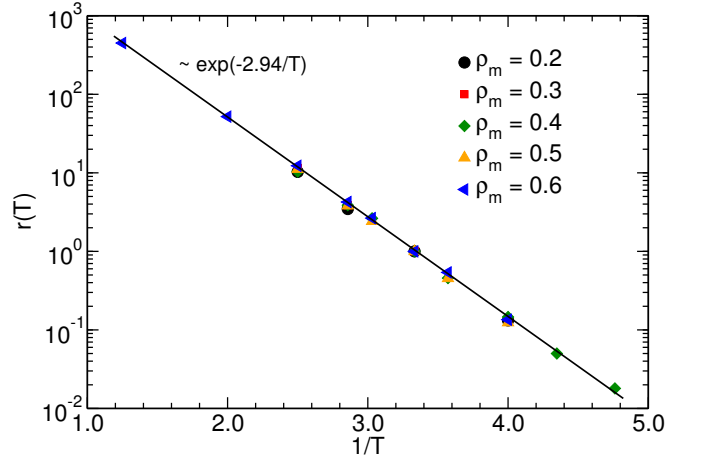


FIG. S2. (Color online) Temperature and density dependence of the scaling factor $r(T)$. Symbols: $r(T)$ used to define the time scale t_B . The scaling factor shows a simple Arrhenius dependence on temperature with an activation energy that is independent of the polymer density ρ_m (solid line).

coarsening process to the creation of large empty cavities. Hence the catalysts can gain entropy by avoiding the dense polymer network and instead move into the cavities. A side effect of this partial phase separation is the reduction of the local density of the catalysts in the polymer rich phase and hence to a decrease in the speed of the A→B conversion (as seen in Fig. 1 for long times).

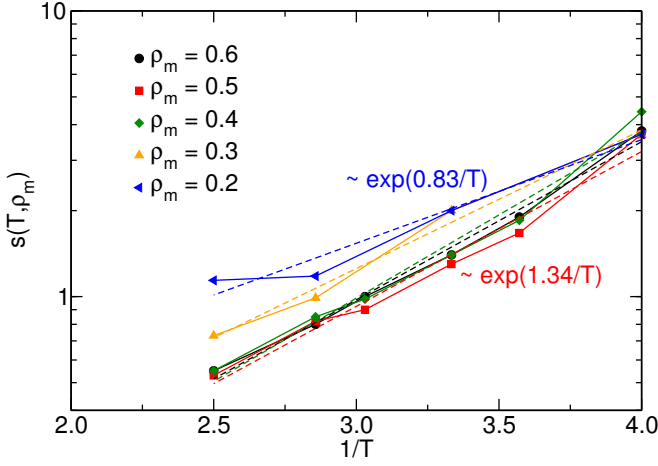


FIG. S3. (Color online) Temperature and density dependence of $s(T, \rho_m)$. Symbols: T -dependence of the scaling factor $s(T, \rho_m)$ for the different values of ρ_m . Within the accuracy of the data this dependence is given by an Arrhenius law (dashed lines). The activation energy is ≈ 1.34 for $\rho_m \geq 0.4$ and decreases with ρ_m for $\rho_m < 0.4$.

D: Time scale t_B

To determine the influence of temperature on the kinetics of the reaction $A \rightarrow B$ for a given value of the

monomer density ρ_m , we have superimposed the curves ρ_B/ρ_m shown in the main panel of Fig. 1 by multiplying time by a scaling factor $r(T)$. This results in the master curve shown in the Inset of Fig. 1 and the time scale $t_B = t \cdot N_C/N_m \cdot r(T)$. Figure S2 shows the T -dependence of $r(T)$ for the different polymer number densities ρ_m we have considered. They all nicely follow an Arrhenius law with activation energy $E_B \approx 2.94$, independent of ρ_m . Thus this is evidence that the mechanism for the $A \rightarrow B$ reaction is independent of temperature and density.

E: Time scale t_S

We define an iso-structure time $t_S = t_B \cdot s(T, \rho_m)$ that allows to compare for short and intermediate times the structure of systems at different temperatures. By definition of $s(T, \rho_m)$, systems that have the same value of t_S but are at a different temperature have the same partial structure factors of the B monomers, $S_B(q)$. Figure S3 shows that the scaling factor $s(T, \rho_m)$ has a T -dependence that is given by an Arrhenius law. For $\rho_m \geq 0.4$ the activation energy is a constant and given by $E_s \approx 1.34$ whereas it depends on ρ_m for $\rho_m \leq 0.3$.